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(54) Measurement of wavefront aberrations in a lithographic projection apparatus

(57) A lithographic projection apparatus comprising:

a radiation system (Ex,IN,CO) for supplying a projection beam (PB) of radiation;
a support structure (MT) for supporting patterning means (MA), the patterning means serving to pattern the projection beam according to a desired pattern;
a substratre table (WT) for holding a substrate (W); and
a projection system (PL) for projecting the patterned beam onto a target portion (C) of the substrate; characterized by:
a measurement system for measuring wave front aberrations of the projection system (PL), the measurement system comprising a grating (7) that is movable into the projection beam between the radiation system (Ex,IN,CO) and the projection system (PL), and a pinhole arranged in a pinhole plate (11) that is movable into the projection beam between the projection system (PL) and a detector (13) for detecting light traversing the pinhole.

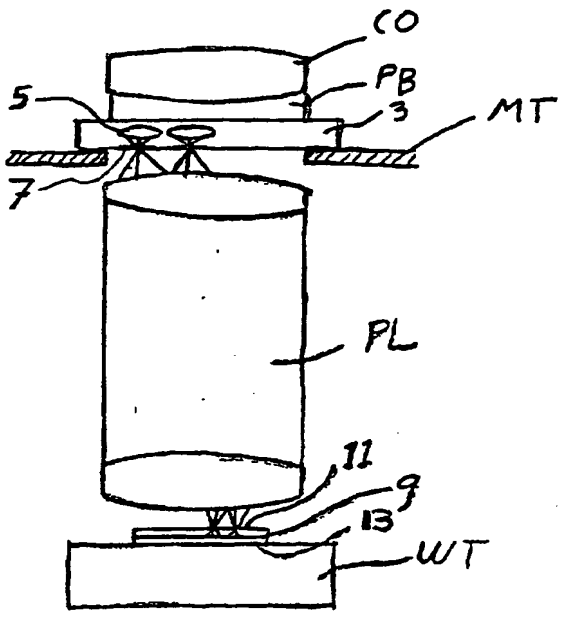


FIG. 2

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[0001] The present invention relates to the measurement of wave front aberrations in lithographic projection apparatus. More particularly, the invention relates to a measurement system for measuring wave front aberrations in lithographic projection apparatus comprising:

a radiation system for supplying a projection beam of radiation;
a support structure for supporting patterning means, the patterning means serving to pattern the projection beam according to a desired pattern;
a substrate table for holding a substrate; and
a projection system for projecting the patterned beam onto a target portion of the substrate.

[0002] The patterning means here referred to should be broadly interpreted as referring to means that can be used to endow an incoming radiation beam with a patterned cross-section, corresponding to a pattern that is to be created in a target portion of the substrate; the term "light valve" can also been used in this context. Generally, the said pattern will correspond to a particular functional layer in a device being created in the target portion, such as an integrated circuit or other device (see below). Examples of such patterning means include:

- A mask. The concept of a mask is well known in lithography, and it includes mask types such as binary, alternating phase-shift, and attenuated phase-shift, as well as various hybrid mask types. Placement of such a mask in the radiation beam causes selective transmission (in the case of a transmissive mask) or reflection (in the case of a reflective mask) of the radiation impinging on the mask, according to the pattern on the mask. In the case of a mask, the support structure will generally be a mask table, which ensures that the mask can be held at a desired position in the incoming radiation beam, and that it can be moved relative to the beam if so desired.
- A programmable mirror array. An example of such a device is a matrix-addressable surface having a viscoelastic control layer and a reflective surface. The basic principle behind such an apparatus is that (for example) addressed areas of the reflective surface reflect incident light as diffracted light, whereas unaddressed areas reflect incident light as undiffracted light. Using an appropriate filter, the said undiffracted light can be filtered out of the reflected beam, leaving only the diffracted light behind; in this manner, the beam becomes patterned according to the addressing pattern of the matrix-adressable surface. The required matrix addressing can be performed using suitable electronic means. More information on such mirror arrays can be gleaned, for example, from United States Patents US 5,296,891 and US 5,523,193, which are incorporated herein by reference. In the case of a programmable mirror array, the said support structure may be embodied as a frame or table, for example, which may be fixed or movable as required.
- A programmable LCD array. An example of such a construction is given in United States Patent US 5,229,872, which is incorporated herein by reference. As above, the support structure in this case may be embodied as a frame or table, for example, which may be fixed or movable as required.

For purposes of simplicity, the rest of this text may, at certain locations, specifically direct itself to examples involving a mask and mask table; however, the general principles discussed in such instances should be seen in the broader context of the patterning means as hereabove set forth.

[0003] Lithographic projection apparatus can be used, for example, in the manufacture of integrated circuits (ICs). In such a case, the patterning means may generate a circuit pattern corresponding to an individual layer of the IC, and this pattern can be imaged onto a target portion (comprising one or more dies) on a substrate (silicon wafer) that has been coated with a layer of radiation-sensitive material (resist). In general, a single wafer will contain a whole network of adjacent target portions that are successively irradiated via the projection system, one at a time. In current apparatus, employing patterning by a mask on a mask table, a distinction can be made between two different types of machine. In one type of lithographic projection apparatus, each target portion is irradiated by exposing the entire mask pattern onto the target portion in one go; such an apparatus is commonly referred to as a wafer stepper. In an alternative apparatus — commonly referred to as a step-and-scan apparatus — each target portion is irradiated by progressively scanning the mask pattern under the projection beam in a given reference direction (the "scanning" direction) while synchronously scanning the substrate table parallel or anti-parallel to this direction; since, in general, the projection system will have a magnification factor M (generally < 1), the speed V at which the substrate table is scanned will be a factor M times that at which the mask table is scanned. More information with regard to lithographic devices as here described can be gleaned, for example, from US 6,046,792, incorporated herein by reference.

[0004] In a manufacturing process using a lithographic projection apparatus, a pattern (e.g. in a mask) is imaged onto a substrate that is at least partially covered by a layer of radiation-sensitive material (resist). Prior to this imaging step, the substrate may undergo various procedures, such as priming, resist coating and a soft bake. After exposure, the substrate may be subjected to other procedures, such as a post-exposure bake (PEB), development, a hard bake and measurement/in-

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spection of the imaged features. This array of procedures is used as a basis to pattern an individual layer of a device, e.g. an IC. Such a patterned layer may then undergo various processes such as etching, ion-implantation (doping), metallization, oxidation, chemo-mechanical polishing, etc., all intended to finish off an individual layer. If several layers are required, then the whole procedure, or a variant thereof, will have to be repeated for each new layer. Eventually, an array of devices will be present on the substrate (wafer). These devices are then separated from one another by a technique such as dicing or sawing, whence the individual devices can be mounted on a carrier, connected to pins, etc. Further information regarding such processes can be obtained, for example, from the book "Microchip Fabrication: A Practical Guide to Semiconductor Processing", Third Edition, by Peter van Zant, McGraw Hill Publishing Co., 1997, ISBN 0-07-067250-4, incorporated herein by reference.

[0005] For the sake of simplicity, the projection system may hereinafter be referred to as the "lens"; however, this term should be broadly interpreted as encompassing various types of projection system, including refractive optics, reflective optics, and catadioptric systems, for example. The radiation system may also include components operating according to any of these design types for directing, shaping or controlling the projection beam of radiation, and such components may also be referred to below, collectively or singularly, as a "lens". Further, the lithographic apparatus may be of a type having two or more substrate tables (and/or two or more mask tables). In such "multiple stage" devices the additional tables may be used in parallel, or preparatory steps may be carried out on one or more tables while one or more other tables are being used for exposures. Twin stage lithographic apparatus are described, for example, in US 5,969,441 and WO 98/40791, incorporated herein by reference.

[0006] There is a desire to integrate an ever-increasing number of electronic components in an IC. To realize this it is necessary to decrease the size of the components and therefore to increase the resolution of the projection system, so that increasingly smaller details, or line widths, can be projected on a target portion of the substrate. For the projection system this means that the projection system and the lens elements used in the projection system must comply with very stringent quality requirements. Despite the great care taken during the manufacturing of lens elements and the projection system they both may still suffer from wave front aberrations, such as, for example, displacement, defocus, astigmatism, coma and spherical aberration across an image field projected with the projection system onto a target portion of the substrate. Said aberrations are important sources of variations of the imaged line widths occurring across the image field. It is important that the imaged line widths at different points within the image field are constant. If the line width variation is large, the substrate on which the image field is projected may be rejected during a quality inspection of the substrate. Using techniques such as phase-shifting masks, or off-axis illumination, the influence of wave front aberrations on the imaged line widths may further increase.

[0007] During manufacturing of a lens element it is advantageous to measure the wave front aberrations of the lens element and to use the measured results to tune the aberrations in this element or even to reject this element if the quality is not sufficient. When the lens elements are put together to form the projection system it may again be necessary to measure the wave front aberrations of the projection system. These measurements may be used to adjust the position of certain lens elements in the projection system in order to minimize wave front aberrations of the total projection system.

[0008] After the projection system has been build into a lithographic projection apparatus, the wave front aberrations may be measured again. Moreover, since wave front aberrations are variable in time in a projection system, for instance, due to deterioration of the lens material or lens heating effects (local heating of the lens material), it may be necessary to measure the aberrations at certain instants in time during operation of the apparatus and to adjust certain movable lens elements accordingly to minimize wave front aberrations. The short time scale, on which lens-heating effects may occur, may require measuring the wave front aberrations frequently.

[0009] An object of the present invention is to provide a measurement system for measuring the wave front aberrations in a lithographic projection apparatus. According to the present invention there is provided a lithographic projection apparatus comprising:

a radiation system for supplying a projection beam of radiation;
a support structure for supporting patterning means, the patterning means serving to pattern the projection beam according to a desired pattern;
a substrate table for holding a substrate; and
a projection system for projecting the patterned beam onto a target portion of the substrate; characterized by:
a measurement system for measuring wave front aberrations of the projection system, the measurement system comprising a grating that is movable into the projection beam between the radiation system and the projection system, and a pinhole arranged in a pinhole plate that is movable into the projection beam between the projection system and a detector for detecting light traversing the pinhole.

[0010] With the measurement system build into the lithographic projection apparatus it is possible to measure the wave front aberrations in the projection system online. The term grating should be interpreted to include any periodic structure. In case the patterning means is

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a mask and the support structure is a mask table for holding the mask the grating can be provided in a grating module that has the same outer extent as a mask. During measurement of the wave front aberrations the grating module may be held at a location where during projection of the patterned beam a mask is held. One of the advantages is that during projection the weight of the grating is not added to the weight of the mask table, such that it is easier to move the mask table.

[0011] Alternatively, it is possible to provide the grating on the support structure at a location away from the location where the patterning means is supported. Whenever it is necessary to measure the aberrations of the projection system the grating can be easily moved into the projection beam to perform the wave front aberration measurement. After the measurement the patterning means is moved into the projection beam and the apparatus can easily continue with projection of the patterned beam onto target portions of the substrate. This possibility is time saving. The patterning means may also be used to pattern the projection beam with a grating pattern in its cross section. This is advantageously because no additional grating has to provided to the apparatus.

[0012] The detector for detecting the light traversing the pinhole from the projection system may be provided on the substrate table. Said pinhole plate may also be provided to the substrate table. One could also provide the pinhole plate and the detector to a sensor module which, during measuring the wave front aberrations, may be provided upon the substrate table at a location where, during the projection of the patterned beam, the substrate is held. After measuring the wave front aberrations of the projection system the sensor module may then be replaced by the substrate, such that the projection of the patterned beam onto the target portions of the substrate may continue. An advantage is that when the sensor and the pinhole plate are build into a sensor module, the weight of the sensor module will not add to the weight of the substrate table and that the sensor doesn't take any space in the substrate table.

[0013] According to a further aspect of the present invention, there is provided a method of measuring wave front aberrations of a projection system in a lithographic projection apparatus comprising:

a radiation system for supplying a projection beam of radiation;
a support structure for supporting patterning means, the patterning means serving to pattern the projection beam according to a desired pattern;
a substrate table for holding a substrate; and
a projection system for projecting the patterned beam onto a target portion of the substrate; characterized in that a method comprising the following steps is used:

providing a grating in the projection beam between the radiation system and the projection system;
providing both a pinhole arranged in a pinhole plate and a detector underneath the projection system such that radiation from the projection beam and traversing the pinhole is detectable by the detector;
illuminating the grating with the projection beam of radiation; and
detecting the radiation traversing the pinhole with the detector.

[0014] This measurement has to be repeated at a particular measurement position a couple of times whereby the grating has to be moved with respect to the pinhole by a phase step in a direction perpendicular to the periodic structures in the gating. The phase step should, preferably, be smaller or equal to 1/3 of the period of the grating. With the term period is meant the distance in which the periodic structures in the grating are repeated. With this measurement one can measure the wave front measurement at a particular measurement position and in a particular direction in the imaged field. To measure the wave front aberrations of the total field on should measure the wave front aberration at a number of measurement points through the imaged field in at least two directions. To move the grating with respect to the pinhole with the phase step it is possible to move the grating and/or to move the pinhole. It is advantageous to move the grating because due to the magnification of the projection system the accuracy requirements for moving the grating above the projection system by the mask table are lower than for moving the pinhole below the projection system.

[0015] The invention also relates to a measurement system for measuring the wave front aberrations of a projection system, said measurement system comprising:

a radiation system for supplying a projection beam of radiation; and
a projection system holder for holding a projection system in the projection beam such that the projection system is illuminated by the projection beam;
characterized in that said measurement system further comprises:

a grating movable into the projection beam in between the radiation system and the projection system holder for diffraction of the projection beam; and
a pinhole arranged in a pinhole plate that is movable into the projection beam between the projection system hold r and a detector for detecting light traversing the pinhole.

[0016] With this system it is possible during the manufacturing of lens elements to measure the wave front

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aberrations of a single lens element and consequently to tune this element or even to reject it if the quality is not sufficient. It is also possible to measure the wave front aberrations of a projection system wherein different lens elements are put together. The results of such a measurement may be used to adjust certain lens elements to minimize the wave front aberrations.

[0017] Although specific reference may be made in this text to the use of the apparatus according to the invention in the manufacture of ICs, it should be explicitly understood that such an apparatus has many other possible applications. For example, it may be employed in the manufacture of integrated optical systems, guidance and detection patterns for magnetic domain memories, liquid-crystal display panels, thin-film magnetic heads, etc. The skilled artisan will appreciate that, in the context of such alternative applications, any use of the terms "reticle", "wafer" or "die" in this text should be considered as being replaced by the more general terms "mask", "substrate" and "target portion", respectively.

[0018] In the present document, the terms "radiation" and "beam" are used to encompass all types of electromagnetic radiation, including ultraviolet radiation (*e.g.* with a wavelength of 365, 248, 193, 157 or 126 nm) and EUV (extreme ultra-violet radiation, *e.g.* having a wavelength in the range 5-20 nm), as well as particle beams, such as ion beams or electron beams.

[0019] Embodiments of the invention will now be described, by way of example only, with reference to the accompanying schematic drawings in which:

Figure 1 depicts a lithographic projection apparatus according to the invention;
Figure 2 shows an embodiment of a wave front aberration measuring system incorporated in the lithographic projection apparatus according to figure 1;
Figure 3A shows a detailed view of a grating module usable in the wave front aberration measurement system of figure 2;
Figure 3B shows a top view upon a two-dimensional grating usable in the grating module of figure 3A;
Figure 4A shows a view of a sensor module for use in the wave front aberration measurement system of figure 2;
Figure 4B shows a top view upon the pinhole plate of the sensor module of figure 4A;
Figure 4C shows a longitudinal section of a pinhole of the sensor module of figure 4A;
Figure 4D shows a detailed view upon the pinhole of figure 4C;
Figure 5A shows a wave front impinging on the grating of the grating module of figure 3A;
Figure 5B shows a wave front traversing the projection system of figure 2;
Figure 5C shows wave front recombination at the sensor module of 4A, and
Figure 6 shows a view of a second embodiment of a sensor module for use in the wave front aberration measurement system of figure 2.

[0020] In the drawings, like references indicate like parts.

Embodiment 1

[0021] Figure 1 schematically depicts a lithographic projection apparatus according to a particular embodiment of the invention. The apparatus comprises:

- a radiation system Ex, IN, CO for supplying a projection beam PB of radiation (*e.g* UV or EUV radiation). In this particular case, the radiation system also comprises a radiation source LA;
- a first object table (mask table) MT provided with a mask holder for holding a mask MA (*e.g.* a reticle), and connected to first positioning means for accurately positioning the mask with respect to item PL;
- a second object table (substrate table) WT provided with a substrate holder for holding a substrate W (*e.g.* a resist-coated silicon wafer), and connected to second positioning means for accurately positioning the substrate with respect to item PL;
- a projection system ("lens") PL (*e.g.* a refractive or catadioptric system, a mirror group or an array of field deflectors) for imaging an irradiated portion of the mask MA onto a target portion C (*e.g.* comprising one or more dies) of the substrate W. As here depicted, the apparatus is of a transmissive type (*i.e.* has a transmissive mask). However, in general, it may also be of a reflective type, for example (with a reflective mask). Alternatively, the apparatus may employ another kind of patterning means, such as a programmable mirror array of a type as referred to above.

[0022] The source LA (*e.g.* a HG lamp, excimer laser, an undulator provided around a path of an electron beam in a storage ring or synchrotron) produces a beam of radiation. This beam is fed into an illumination system (illuminator) IL, either directly or after having traversed conditioning means, such as a beam expander Ex, for example. The illuminator IL may comprise adjusting means AM for setting the outer and/or inner radial extent (commonly referred to as σ-outer and σ-inner, respectively) of the intensity distribution in the beam. In addition, it will generally comprise various other components, such as an integrator IN and a condenser CO. In this way, the beam PB impinging on the mask MA has a desired uniformity and intensity distribution in its cross-section.

[0023] It should be noted with regard to Figure 1 that the source LA may be within the housing of the lithographic projection apparatus (as is often the case when the source LA is a mercury lamp, for example), but that it may also be remote from the lithographic projection apparatus, the radiation beam which it produces being

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led into the apparatus (e.g. with the aid of suitable directing mirrors); this latter scenario is often the case when the source LA is an excimer laser. The current invention and claims encompass both of these scenarios.

[0024] The beam PB subsequently intercepts the mask MA, which is held on a mask table MT. Having traversed the mask MA, the beam PB passes through the lens PL, which focuses the beam PB onto a target portion C of the substrate W. With the aid of the second positioning means (and interferometric measuring means IF), the substrate table WT can be moved accurately, *e.g.* so as to position different target portions C in the path of the beam PB. Similarly, the first positioning means can be used to accurately position the mask MA with respect to the path of the beam PB, *e.g.* after mechanical retrieval of the mask MA from a mask library, or during a scan. In general, movement of the object tables MT, WT will be realized with the aid of a long-stroke module (course positioning) and a short-stroke module (fine positioning), which are not explicitly depicted in Figure 1. However, in the case of a wafer stepper (as opposed to a step-and-scan apparatus) the mask table MT may just be connected to a short stroke actuator, or may be fixed.

[0025] The depicted apparatus can be used in two diff rent modes:

In step mode, the mask table MT is kept essentially stationary, and an entire mask image is projected in one go (*i.e.* a single "flash") onto a target portion C. The substrate table WT is then shifted in the x and/or y directions so that a different target portion C can be irradiated by the beam PB;

In scan mode, essentially the same scenario applies, except that a given target portion C is not exposed in a single "flash". Instead, the mask table MT is movable in a given direction (the so-called "scan direction", *e.g.* the y direction) with a speed v, so that the projection beam PB is caused to scan over a mask image; concurrently, the substrate table WT is simultaneously moved in the same or opposite direction at a speed $V = Mv$, in which M is the magnification of the lens PL (typically, $M = 1/4$ or 1/5). In this manner, a relatively large target portion C can be exposed, without having to compromise on resolution.

[0026] Figure 2 shows a wave front aberration measurement system incorporated in the lithographic projection apparatus according to the invention of figure 1. In this figure the following items of the system can be seen, which are shared with the lithographic projection apparatus: condensor lens CO, mask table MT, projection system PL, and wafer table WT. Further the aberration measuring system comprises the following items;

- a grating module 3 which may be put on the mask table MT occasionally, or which may form a part of said table, said grating module 3 comprising a grating module lens 5 and a grating 7; and
- a sensor module 9 which may be put on the substrate table WT occasionally or which may form a part of said substrate table WT, said sensor module 9 comprising a detector 13 and a pinhole plate 11.

[0027] Figure 3A shows a more detailed view on the grating module 3. The grating module 3 is illuminated with a substantially uniform and parallel projection beam PB from the illuminator IL. The grating module lens 5 focuses this beam upon the grating 7 such that the uniform illumination over the field of the projection beam PB is transferred into substantial uniformity of illumination over the angles. One of the advantages of using this lens is that the intensity in the focal point of the lens 5 is increased. The grating diffracts the focused illumination which traverse through the projection system PL. The grating module lens is chosen such that the zeroth diffraction order of the beam fills the total pupil plane of the projection system PL. The latter is necessary to assure that the measurement result comprises the total wave front aberrations distributed over the total pupil plane of the projection system PL. The grating 7 may be chosen such that -1^{st} and $+1^{st}$ diffraction order at least overlap a little in the pupil plane of the projection system PL. Grating 7 may be a 2-dimensional grating as is shown in figure 3B, however, it is also possible to use two one dimensional gratings with a different orientation with respect to each other. The use of a two-dimensional grating is advantageous, because one two-dimensional grating can be used for taking samples in two directions perpendicular to each other. The arrows 25 and 27 show two directions in which the grating 7 can be moved (i.e. phase stepped) through the projection beam PB between two samples. One sample comprises a number of pulses that are radiated by the radiation system through the grating 7, the projection system PL and the pinhole plate 11 upon the detector 13. After a first sample the grating 7 has to be moved (i.e. phase stepped) with respect to the pinhole plate with a phase step. The phase step is chosen such that at least three samples are taken before the grating 7 is moved with a distance equal to one period. The period of the grating in direction 25 is equal to the distance denoted by P. Grating 7 comprises two different regions 23 and 21, both regions having a different transmission or causing a phase shift in the traversing radiation to diffract the radiation.

[0028] Figure 4A shows a more detailed view on an embodiment of a sensor module 9. Light from the projection system PL is focussed upon a pinhole 17 provided in the pinhole plate 11 and is subsequently detected by detector 13. Figure 4B depicts a top view upon the pinhole plate 11 and the pinholes 17. There are two pinholes 17 provided to the pinhole plate 11; each pinhole is for measuring in the phase step direction as depicted by its respective arrows 25 or 27. It should be noted that the phase step directions depicted by the arrows 25 and

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27 in figure 3B corresponds with the arrows 25 and 27 in figure 4B. Figure 4C shows a detailed longitudinal section of one of the pinholes in figure 4B. The arrow 25 shows the direction, in which the pinhole17 should be phase stepped. The radiation focussed upon the pinhole 17 will be diffracted and detected by the detector 13. The area denoted by 45 receives radiation from the -1st diffraction order, the area denoted by 47 receives radiation from the zeroth diffraction order and the area denoted by 49 receives radiation from the + 1st diffraction order.

[0029] During the wave front aberration measurement the grating module 3 is stepped through the projection beam PB in a first direction with small phase steps to measure the wave front aberration at a particular fixed measurement point in the imaged field. This measurement has to be repeated for another, second direction at said particular point. For this purpose we can use the two-dimensional 7 grating which may be used in the first and second directions depicted by the arrows 27 and 25, respectively in figure 3B. The pinholes 17 in the pinhole plate 11 are one-dimensional and therefore it is necessary to use two pinholes, one for measurements in the first direction 27 and a second pinhole for measurements in the second direction 25. For a complete measurement of the wave front aberration over the total image field, the wave front aberration measurement should be repeated in the first and second direction at a number of measurement points distributed over the image field. Figure 4D shows a detailed view upon the pinhole 17. The aerial image 41 of the grating 7 on the pinhole plate 11 is also shown. This aerial image has a period P2 that depends on the period P of the grating and the magnification M of the projection system PL according to the formula:

$$P2 = P \times M$$

[0030] The size of the pinhole 17 should preferably be smaller than half of the distance P2, because otherwise the intensity measured by the detector 13 would be averaged and detector 13 would become less sensitive. For improving the sensitivity of the detector 13 it is possible to provide more pinholes 17 to the pinhole plate 11. These additional pinholes should be located parallel to the pinholes 17 in figure 4B and at a distance equal to P2 from the pinholes 17, such that all pinholes measure the same phase from the grating 7. Further, the pinhole 17 should be phase stepped with respect to the image 41 of the grating 7 in at most steps of 1/3 of P2. By phase stepping the pinhole 17 through the image 41 the spatial intensity distribution of radiation, received at the pinhole 17, from the image 41 will be measured. The detector 13, which for example may be a two-dimensional sensor array such as a CCD camera, will measure the total energy received through the pinhole 17 upon integrating the signal over th whole detector surface. The detector 13 will also measure the energy of radiation received out of a particular direction, because the different areas (the different pixels in case of a CCD) of the detector 13 will measure the energy of the radiation received from a particular direction out of the pupil plane, as defined geometrically by the relative position of the pinhole 17 with respect to the area in question.

[0031] In figure 5A the projection beam impinging on the grating 7 is shown. The wave WI can be considered as a Fourier sum of plane waves PW (1,i), [i=0,1,2...]. The wave emanating from grating 7, WD, can be considered as a sum of diffracted plane waves PW (2,i), [i=0,1, 2...]. PW (22), PW (20) and PW (21) are, respectively, the +1st, zeroth and -1st diffracted order of the incoming wave PW (10). In the projection system PL (see figure 5B) the plane waves PW (2i), [i=0, 1, 2...] will focus near or at the pupil plane PU, and sample the pupil plane in three points. The lens aberrations can be thought of as phase errors that are endowed on the focussed plane waves PW (2i), [i=0, 1, 2....] in the pupil plane. These focussed plane waves will exit the lens as plane waves PW (3i), [i= 0, 1, 2....], respectively. To measure the phase errors representing for the lens aberrations, the plane waves PW (3i), [i= 0,1, 2....] are directionally recombined by diffraction at slit 17 see figure 5C. For instance, PW (400) is the zeroth order diffracted wave originating from PW (30), PW (411) is the +1st order diffracted wave from PW (31) and PW (422) is the -1st order diffracted wave originating from PW (32) and these directionally recombined waves can interfere. Their interference intensity is harmonic with the phase stepping of grating 7. Other recombination's of diffracted waves originating from the PW (3i) [i=0.1.2...], are possible as well. However, the intensity resulting from the interference of such recombination varies as a higher harmonic of the phase stepping movement of grating 7. By filtering out these higher order harmonic signals from each CCD-pixel signal one obtains the result that each CCD-pixel signal is representative for a three point sampling of the aberration in the pupil, as explained.

[0032] The embodiment of Figure 6 makes use of an additional lens 15 to focus the light upon the detector 13. For this purpose one lens 15 or a set of lenses may be used. When a set of lenses is used they may be configured similar to a microscope objective. The detector 13 may take the form of a CCD camera connected to a processing unit comprising a calculation device and a memory device. The processing unit may be used to calculate the pixel positions measured by the CCD camera to pupil positions and to store this data in the memory device.

[0033] In an alternative measurement system the grating 7 can be positioned above the detector 13 instead of the pinhole plate, the pinhole plate 11 with the pinhole 17 should then be positioned between the radiation system and the projection system PL instead of the grating 7. The detector 13 will in that case be more sensitive to stray light (i.e. light reflected internally in the

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projection system PL and reflected to the detector 13), which will decrease the sensitivity of the detector 13. Further, with a pinhole plate 11 located between the radiation system and the projection system PL the use of lenses 5 to focus the light upon the pinhole 17 make it necessary to align the lenses very precisely with the holes 17 in the pinhole plate 11. If this is not done precisely, intensity is lost and then it takes more time to measure the wave front aberrations. It must be understood that the alternative wave front aberration measurement system as described in this paragraph and the wave front aberration measurement system according to the invention can be used to measure the wave front aberration at a particular fixed measurement position. Different measurement scenario's can be used to measure the wave front aberration at different measurement points in a total image field, as explained below.

[0034] If the lithographic apparatus in which the wave front aberrations have to be measured is a stepper, the mask table MT is in general not movable. During projection an entire mask image is projected in one go (*i.e.* a single "flash") onto a target portion C. The grating will in that case be kept stationary on the mask table and the number of measurement points which can be measured is equal to the number of illuminated points on the grating 7. For example, if we would like to measure the wave front aberration in a stepper at twenty measurement points in the image field we should use twenty grating module lenses 5 to focus their light upon twenty measurement points upon the grating 7. The pinhole plate 11 and the sensor 13 on the substrate table WT should be moved by the substrate table WT, so that the pinhole 17 in the pinhole plate 11 is moved into each of the twenty individual measurement points projected by the projection system PL and subsequently stepped through those individual measurement points with phase steps to measure the wave front aberration at each individual measurement point. The measurement should be done in first and second directions at each individual measurement point so we could, advantageously, use a second pinhole in the pinhole plate 11. The same measurement scenario may apply in the alternative measurement system wherein the pinhole plate 11 is located between the radiation system and the projection system PL and the grating 7 is positioned between the detector 13 and the projection system PL. The substrate table WT should move the grating 7 and detector 13 in that case to every measurement point and phase step the grating 7 at said measurement point in two directions.

[0035] The above mentioned measurement scenario may also be used when the lithographic projection apparatus is a scanner. In a scanner both the mask table MT and the substrate table WT are movable. The phase steps could advantageously be accomplished by moving the grating 7 with the mask table MT because, due to the magnification (typically in de order of 1/4 and 1/5) of the proj ction system PL the accuracy requirements for moving the grating 7 above the projection system PL, with the mask table MT are lower than for moving the pinhole plate 11 and detector 13 below the projection system PL with the substrate table WT. Another advantage is that each pixel of the detector 13 (e.g. a CCD camera) underneath the pinhole plate 11 will in that case measure the same pupil position during each phase step. This relaxes the accuracy requirements for calibration of the CCD, because the intensity of a particular pupil position is measured with the same pixel having the same error during each phase step. To measure the wave front aberration at different measurement points over the image field, the pinhole plate 11 and the detector 13 may be moved through the image field to every individual point and measure the wave front aberration at said point by phase stepping of the grating 7. This scenario could also be used in the alternative measurement system wherein the pinhole plate 11 is located between the radiation system and the projection system PL and the grating 7 and the detector 13 underneath the projection system PL. In that case the mask table MT should move the pinhole plate 11 in the phase stepping direction.

[0036] Measuring a scanned wave front in a scanner may follow another different measurement scenario. This scenario can be used in a measurement system according to the invention having a grating between the radiation and projection system PL and a pinhole 17 and detector 13 underneath the projection system PL, and in the alternative measurement system having a pinhole 17 between the radiation and projection system PL and a grating 7 and detector 13 underneath the projection system PL. Using this scenario in the measurement system according to the invention the grating 7 will be moved simultaneously with the pinhole 17 and detector 13 during each sample, the pinhole 17 and detector 13 will be moved with a speed equal to the to the magnification times the speed of the grating 7. The direction of movement of the grating 7 with respect to the pinhole 17 and the detector 13 will be chosen such that the image 41 of the grating 7 projected upon the pinhole 17 will move in the same direction and with the same speed as the pinhole 17 and the detector 13 do. After a first sample is taken the grating 7 is moved with respect to the pinhole 17 and detector 13 with a phase step and a second sample is taken by moving the grating, again simultaneously with the pinhole 17 and detector 13. This will be repeated for a number of samples. Each pixel of the detector 13 underneath the pinhole plate 11 will in that case measure the same pupil position during each phase step, which relaxes the accuracy requirements for calibration of the CCD. Another advantage is that the wave front aberration measurement thus obtained is an integrated wave front aberration measurement through the slit in the scanning direction. The measurement will only be repeated for different positions in a direction perpendicular to the scanning direction to obtain a total wave front aberration measurement.

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[0037] The measurement results thus obtained may be used during production of lens elements to tune the form of the lens elements. If the lens element is mounted in the projection system one could also consider alteration of position of the different lens elements with respect to each other. When the projection system is integrated in the lithographic projection apparatus, the measurement result of the wave front aberration measurement may, further be used to adjust the wavelength of the projection beam of radiation or the distance between the mask table and the projection system. Lens elements within the projection system may also be build spatially adjustable to minimize the aberrations. For particular lens designs, for example in Extreme Ultra Violet and for Ultra Violet with a wavelength of 157 nm, the use of mirrors in the projection system is considered. The shape of said mirrors may be largely determined by actuators between the backside of the mirror and a stiff frame element supporting said mirror. The input of the wave front aberration measurement system may be used to adjust the form of the mirrors such that the wave front aberrations in the projection beam are minimized.

[0038] Whilst we have described above a specific embodiment of the invention it will be appreciated that the invention may be practiced otherwise than described. The description is not intended to limit the invention.

Claims

1. A lithographic projection apparatus comprising:

 a radiation system for supplying a projection beam of radiation;
 a support structure for supporting patterning means, the patterning means serving to pattern the projection beam according to a desired pattern;
 a substrate table for holding a substrate; and
 a projection system for projecting the patterned beam onto a target portion of the substrate;
 characterized by:

 a measurement system for measuring wave front aberrations of the projection system, the measurement system comprising a grating that is movable into the projection beam between the radiation system and the projection system, and a pinhole arranged in a pinhole plate that is movable into the projection beam between the projection system and a detector for detecting light traversing the pinhole.

2. A lithographic projection apparatus according to claim 1, wherein the patterning means is a mask and the support structure is a mask table.

3. A lithographic projection apparatus according to claim 2, wherein the measurement system comprises a grating module to be held by the mask table at a location for holding the mask, the grating being provided in the grating module.

4. A lithographic projection apparatus according to claim 1, wherein said grating is provided on the support structure at a location away from a location for holding the patterning means.

5. A lithographic projection apparatus according to claim 1, wherein the measurement system comprises means for patterning the patterning means with a grating.

6. A lithographic projection apparatus according to any of the proceeding claims, wherein said measurement system further comprises a lens having a focal distance, said lens being positioned between the radiation system and the grating at a distance to the grating which is substantially equal to the focal distance of the lens.

7. A lithographic projection apparatus according to any of the proceeding claims, wherein said detector is provided on the substrate table.

8. A lithographic projection apparatus according to any one of the proceeding claims, wherein said pinhole plate is provided on the substrate table.

9. A lithographic projection apparatus according to any one of claims 1 to 6, wherein the measurement system comprises a sensor module to be held by the substrate table at a location for holding the substrate, said sensor module comprising the detector and the pinhole plate.

10. A grating module for use in a lithographic projection apparatus according to claim 3.

11. A sensor module for use in a lithographic projection apparatus according to claim 9.

12. A method of measuring wave front aberrations of a projection system in a lithographic projection apparatus comprising:

 a radiation system for supplying a projection beam of radiation;
 a support structure for supporting patterning means, the patterning means serving to pattern the projection beam according to a desired pattern;
 a substrate table for holding a substrate; and
 a projection system for projecting the patterned beam onto a target portion of the substrate;

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characteriz d in that the method comprises the following steps:

providing a grating in the projection beam between the radiation system and the projection system;
providing both a pinhole arranged in a pinhole plate and a detector underneath the projection system such that radiation from the projection beam and traversing the pinhole is detectable by the detector;
illuminating the grating with the projection beam of radiation; and
detecting the radiation traversing the pinhole with the detector.

13. A method according to claim 12, wherein said grating has a grating period in a first direction and the grating is stepped after detecting the radiation at a particular phase of the grating in said first direction to repeat detecting the radiation at a different phase of the grating.

14. A method according to claim 13, wherein the grating is stepped in said first direction with a phase step of at most 1/3 of the grating period.

15. A method according to claim 12, wherein said grating has a grating period in a first direction and the pinhole plate and the detector are stepped after detecting the radiation at a particular phase in said first direction to repeat detecting the radiation at a different phase of the grating.

16. A method according to claim 12, wherein said grating has a grating period in a first direction and during detecting the radiation traversing the pinhole the support structure and the substrate table are moved in a direction parallel to said first direction, the substrate table having a speed equal to the magnification of the projection system times the speed of the support structure.

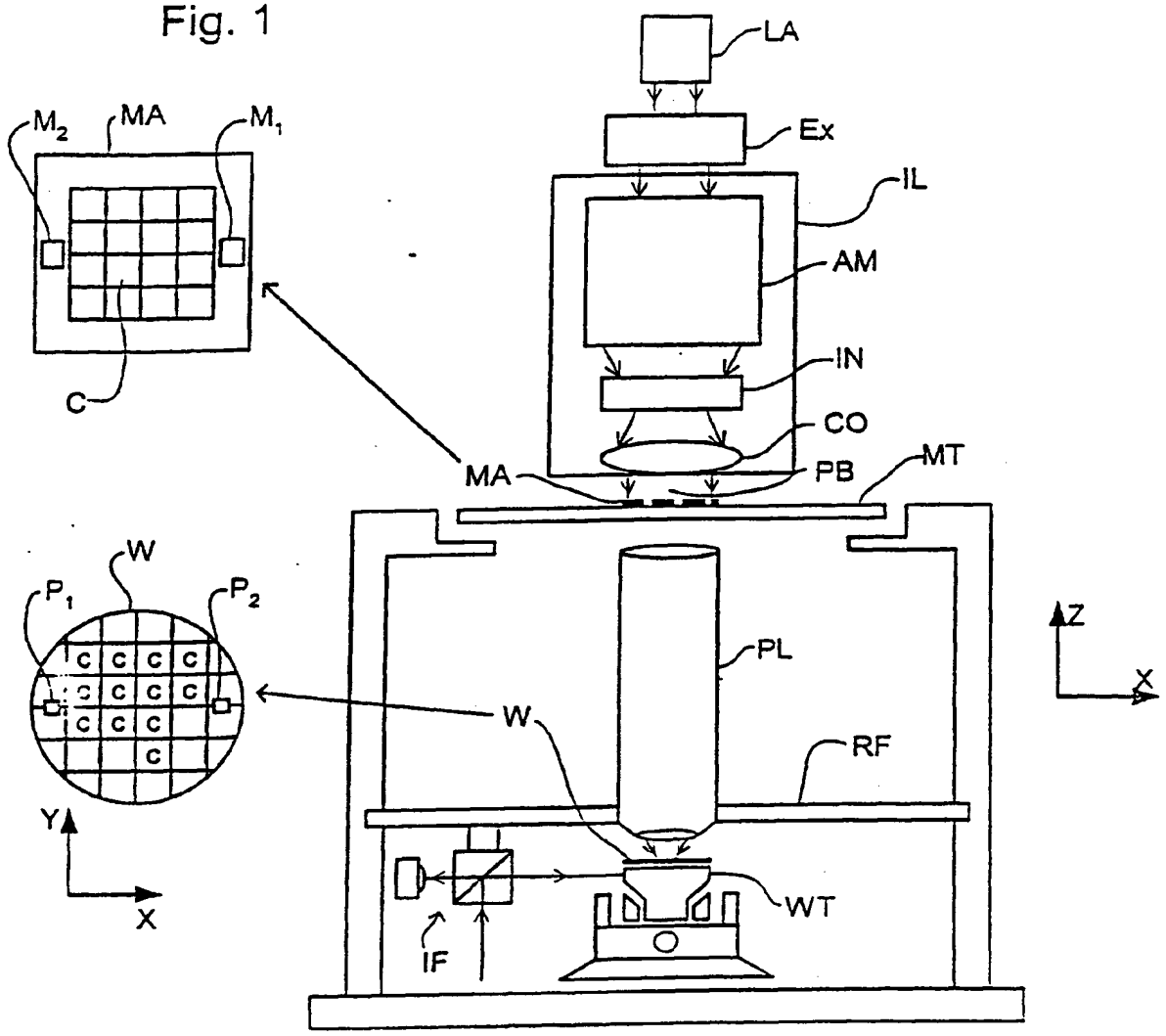
17. A measurement system for measuring wave front aberrations of a projection system, said measurement system comprising:

a radiation system for supplying a projection beam of radiation; and
a projection system holder for holding a projection system in the projection beam such that the projection system is illuminated by the projection beam; **characterized in that** said measurement system further comprises:

a grating movable into the projection beam in between the radiation system and the projection system holder for diffraction of the projection beam; and
a pinhole arranged in a pinhole plate that is movable into the projection beam between the projection system holder and a detector for detecting light traversing the pinhole.

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Fig. 1



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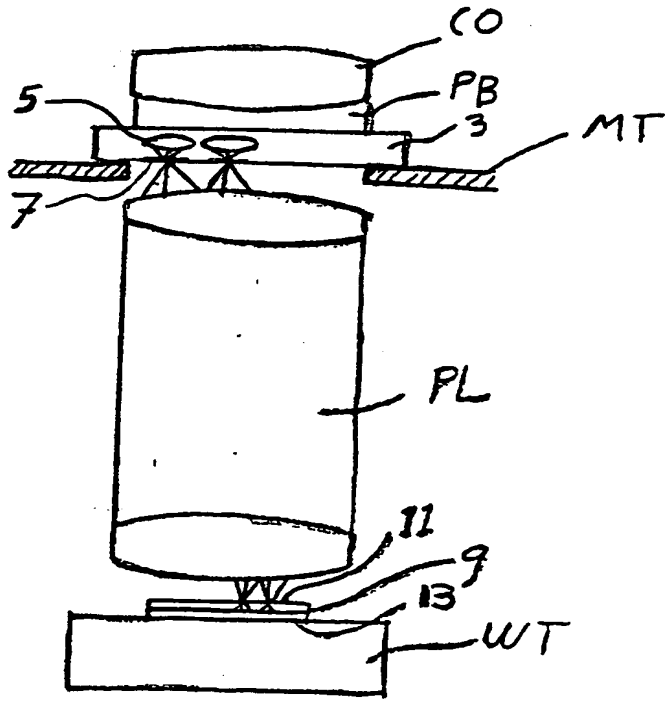


FIG. 2

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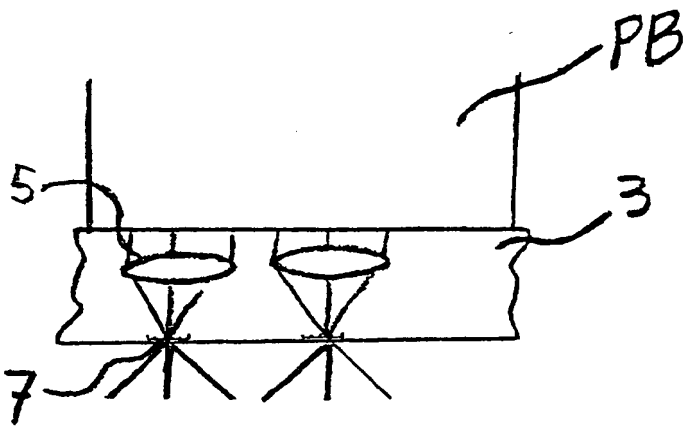


FIG. 3A

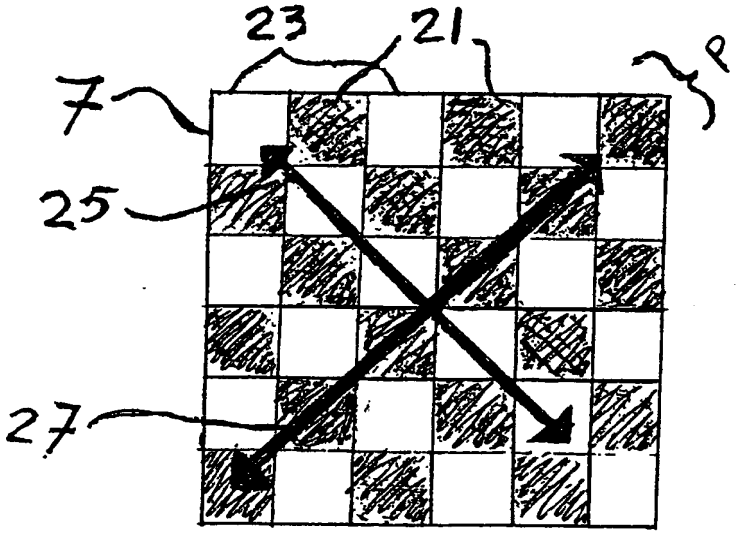


FIG. 3B

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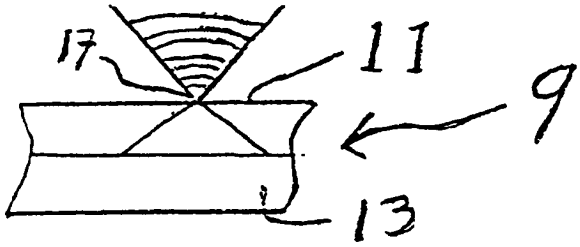


FIG. 4A

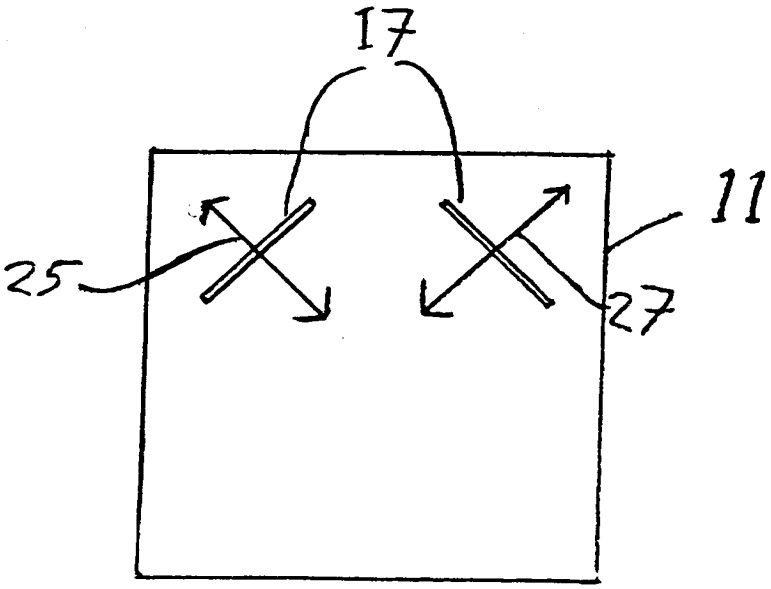


FIG. 4B

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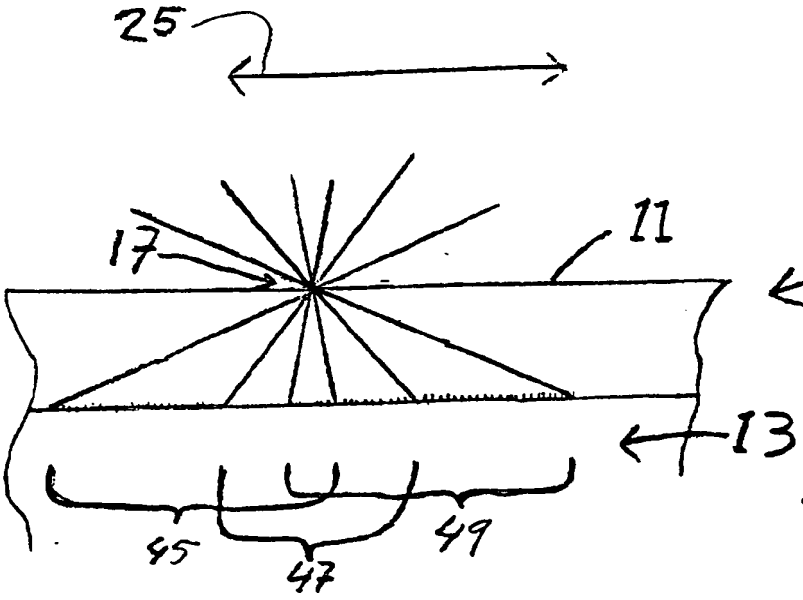


FIG.4C

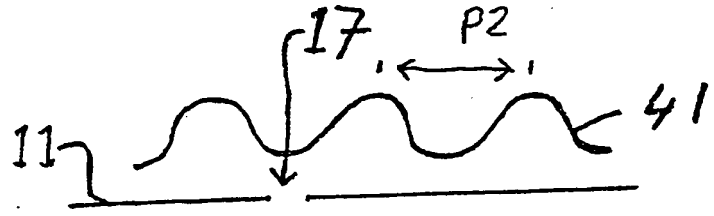


FIG.4D

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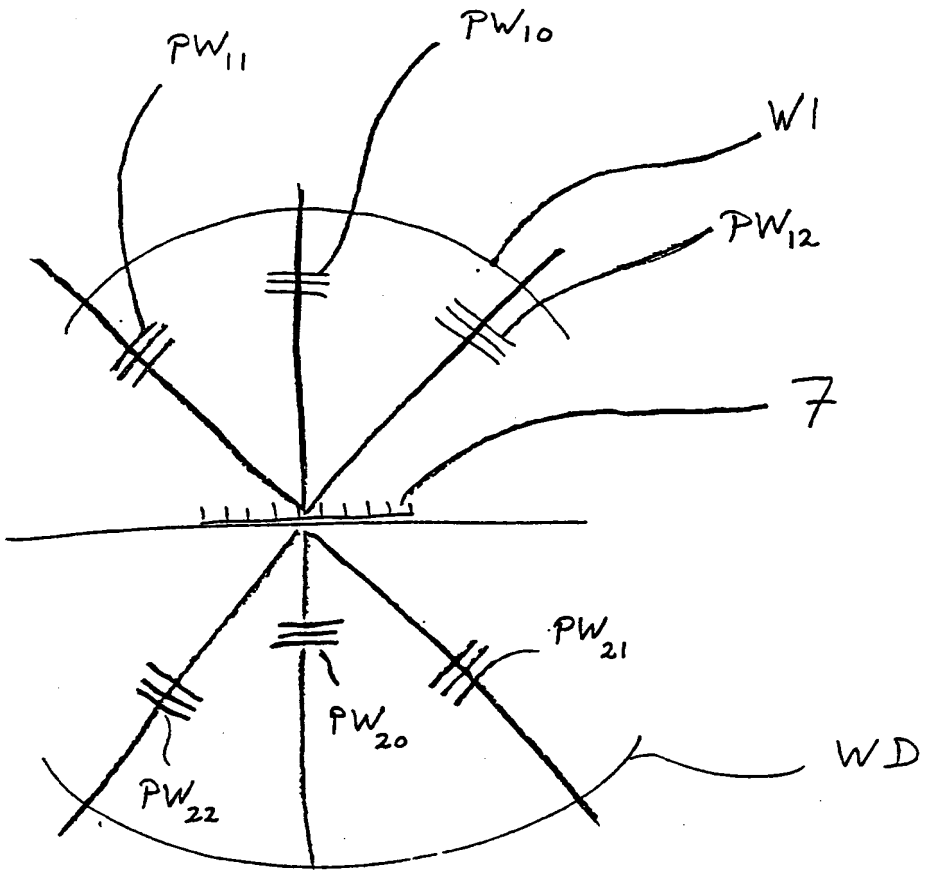


FIG 5A

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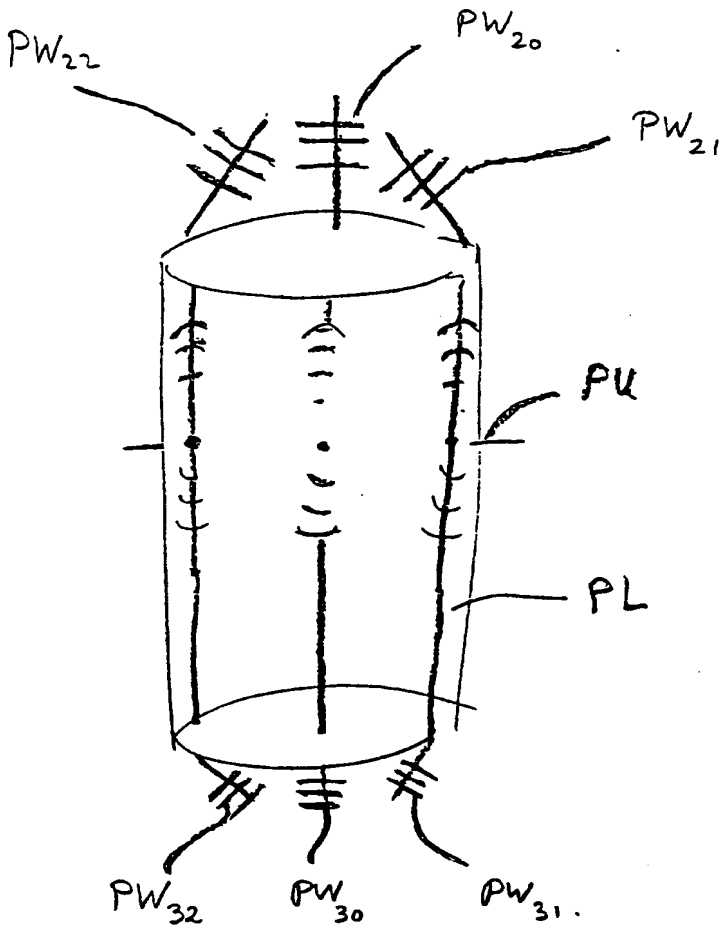


FIG 5B

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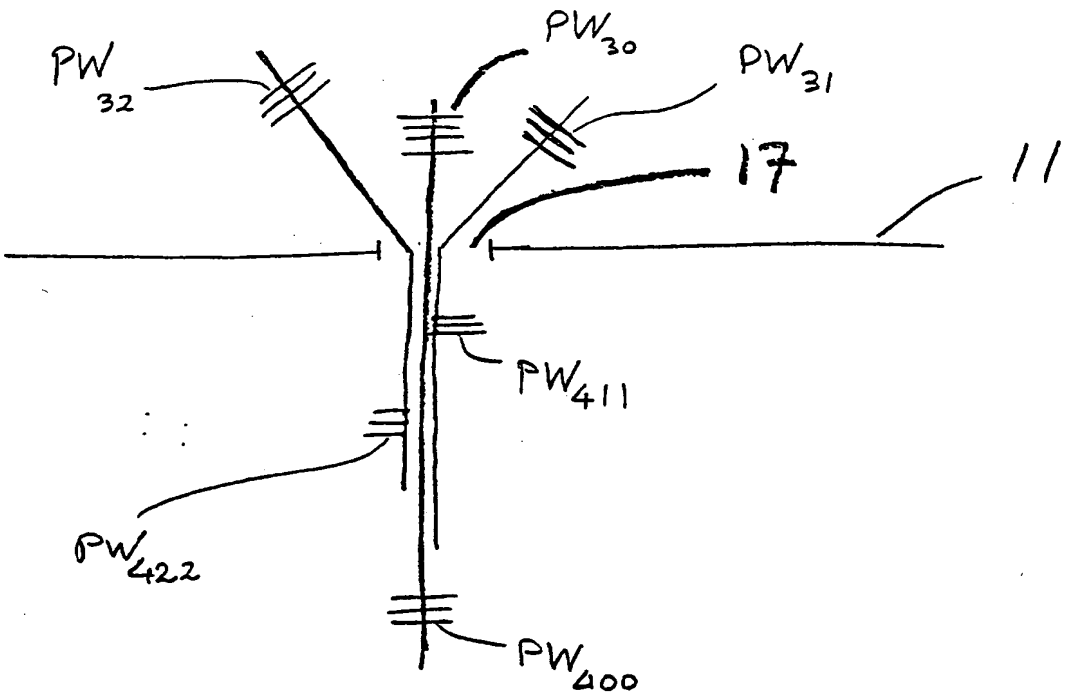


FIG 5C

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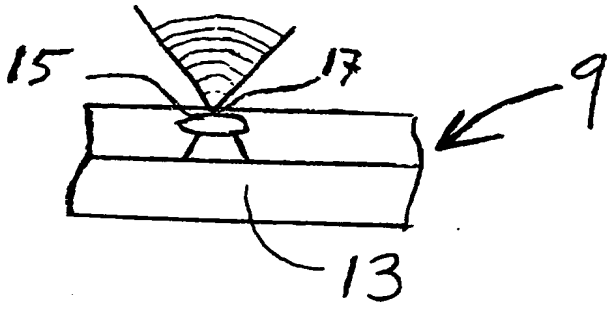


FIG. 6

BNSDOCID: <EP___1231514A1_I_>

European Patent Office

EUROPEAN SEARCH REPORT

Application Number
EP 01 30 1283

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Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.7)
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X	US 6 118 535 A (GOLDBERG KENNETH ALAN ET AL) 12 September 2000 (2000-09-12) * column 5, line 29 - column 6, line 31 * * figure 2 *	1-17	

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G01M

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	8 August 2001	Heryet, C

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For more details about this annex : see Official Journal of the European Patent Office, No. 12/82

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CLIENT REF.: P-0364.010-US
FILED: September 26, 2003
TITLE: LITHOGRAPHIC APPARATUS AND A ...

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